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On-chip multi spectral frequency standard replication by stabilizing a microring resonator to a molecular line

Roy Zektzer, Liron Stern, Noa Mazurski, and Uriel Levy

Department of Applied Physics, The Benin School of Engineering and Computer Science, The Center for Nanoscience and Nanotechnology, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

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Stabilized laser lines are highly desired for myriad of applications ranging from precise measurements to optical communications. While stabilization can be obtained by using molecular or atomic absorption references, these are limited to specific frequencies. On the other hand, resonators can be used as wide band frequency references. Unfortunately, such resonators are unstable and inaccurate. Here, we propose and experimentally demonstrate a chip-scale multispectral frequency standard replication operating in the spectral range of the near IR. This is obtained by frequency locking a microring resonator (MRR) to an acetylene absorption line. The MRR consists of a Si3N4 waveguides with microheater on top of it. The thermo-optic effect is utilized to lock one of the MRR resonances to an acetylene line. This locked MRR is then used to stabilize other laser sources at 980 nm and 1550 nm wavelength. By beating the stabilized laser to another stabilized laser, we obtained frequency instability floor of $4 \times 10^{-15}$ at around 100 s in terms of Allan deviation. Such stable and accurate chip scale sources are expected to serve as important building block in diverse fields such as communication and metrology. Published by AIP Publishing.

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Frequency stabilized sources are required for precision measurement instruments such as wavemeters and frequency synthesizers. There is also a need for multiple stabilized frequency sources in the telecom spectral range in order to construct a dense wavelength division multiplexing system. While lasers at wavelengths such as 780 nm, 795 nm, 895 nm, and 589 nm can be referenced by Rubidium and Cesium atoms absorption lines, and acetylene ($^{12}$C2H2) absorption lines can be used as references for certain telecom wavelength, many other sources have no reference, and therefore, these sources should be calibrated repeatedly.

In order to transfer the frequency accuracy from one spectral band to another, one can use nonlinear effects such as second harmonic generation and two photon absorption. While these effects result in a single line source, great progress has been achieved in generating stabilized frequency combs providing multiple lines with frequency instability of $10^{-15}$. A well-established approach for the stabilization of laser frequency and frequency transfer is the locking of a resonator to an atomic or molecular reference.

It is well known that the instability of a locked system can significantly exceed the relative linewidth (defined as $\Delta \nu/\nu = 1/(Q)$). Assuming a white noise limited system, the effective signal to noise ratio improves with the square root of the integration time of the system (up to the point where the system is no longer white noise limited). Thus, the instability of such a system is given by $\sigma_{\nu}(\tau) = 0.2 \times N/(Q \times S) \times \tau^{0.5}$ where N is the noise, S is the signal, $\tau$ is the averaging time, and Q is the Q factor of the local oscillator.

Hereby, we propose and demonstrate a chip-scale based optical frequency reference which is capable of transferring frequency stability from one spectral band to another. Specifically, we demonstrate the frequency stability transfer from a molecular line in the telecom spectral range, to the near infrared spectral range around 980 nm. This is achieved by the frequency locking of a microring resonator (MRR) to an acetylene absorption line and transferring its frequency stability to the MRR lines. Our MRR supports both the telecom and the 980 nm bands. As such, we can now lock a 980 nm laser source to one of the stabilized MRR lines. By doing so, we could have obtained a stable 980 nm line, up to the accuracy of our measurement system. To better evaluate the metrics of our approach, we have replaced the 980 nm source by another telecom laser and evaluate its achieved stability by comparing it to another acetylene line. Using this approach, we obtained instability down to the $4 \times 10^{-15}$ level (corresponding to 800 KHz) at $\tau = 34$ s. Such instability is very close to the directly measured instability of our acetylene cell stabilization system.

Our device (Fig. 1(a)) consists of a Si3N4 microring resonator with a radius of 80 $\mu$m and a cross section of 0.5 $\mu$m height by 1 $\mu$m width. The Si3N4 is grown on top of a 2 $\mu$m thick thermal oxide using plasma enhanced chemical vapor deposition (PECVD) and is covered by another 2 $\mu$m thick SiO2 layer. Aluminum contacts were fabricated on top of the device to provide frequency tuning of $\sim 10^{-5}$ per degree Kelvin in normalized frequency units, via the thermo-optic effect, with the end result of 1 GHz/V. This value may slightly shift with wavelength as a result of waveguide dispersion. The heaters consist of 40 $\mu$m wide and 200 nm thick aluminum stripes on top of the upper SiO2 layer and surrounding the MRR with resistance of about 10 $\Omega$ (Fig. 1(b)). Our MRR supports spectral ranges both at the telecom (Fig. 1(c)) and at 980 nm (Fig. 1(d)). Our MRR has a Q factor of $\sim 10^5$ and FSR of $\sim 2.5$ nm as can be seen in Fig. 1(c).
This results in a finesse of $\sim 165$. We have coupled light to our device by using standard tapered couplers resulting in a 7 dB coupling losses. We have measured the settling time of our heaters to be $\sim 1$ ms.

The stabilization transfer scheme is presented in Fig. 2. A tunable laser at telecom wavelength (HP 81682A) is stabilized using a wavelength modulation scheme $^{18,20}$ to an acetylene line (1534.0987 nm P15). We have used a 50 Torr reference cell which results in a relatively broad ($\sim 1$ GHz) absorption line. Next, we lock one of the MRRs resonance frequencies at the telecom regime to the same laser taking advantage of the thermo-optic effect such that the resonance frequency of the MRR is controlled by the heaters. Finally, another tunable laser, this time around 980 nm (New Focus “Velocity”) is locked to one of the MRR resonances. In order to implement this chain of servo-loops, each of our external cavity tunable lasers are wavelength modulated by injecting a current into their built in piezo element. The 1550 nm laser is modulated at 1 KHz, with a modulation depth corresponding to $\sim 50$ MHz. This applied modulation is used both to tune the laser to the acetylene absorption line, and in order to tune the MRR to the laser. A bias voltage is applied to the microheaters in order to initialize the detuning of MRRs resonances. The servo loop is implemented by injecting the integrated output of the Lock In Amplifier (LIA) (fed by the detector connected to the output of the MRR) to the microheaters. As illustrated in Fig. 2, both the 980 nm and the 1550 nm laser signals are detected using the same photodetector. In order to differentiate between the two signals, the 980 nm laser is modulated at a different frequency of 800 Hz with a modulation depth corresponding to $\sim 50$ MHz. The integrators are realized by field programmable gate array (FPGA, NI cRIO-9074). The overall time constant of the servo loops using this realization is 100 ms.

In order to verify that we indeed stabilized a 980 laser to the acetylene cell, we applied a deliberate frequency shift (by applying a ramp voltage to the laser’s piezo system) to the 980 nm laser while applying our feedback loop. In Fig. 3(a), we present the laser frequency detuning (measured using an optical spectrum analyzer ADVANTEQ Q8384) in the case where the servo loops are active (blue line), and as a reference also for the case where the servo loops are deactivated. One can clearly observe that the locked laser maintains its frequency stability better than the unlocked one, which deviates significantly. This measurement shows the ability of our system to overcome large frequency drifts. The spectrum analyzer has a resolution of 10 pm which results in triangular features on both lines. Next, we compare (Figs. 3(b) and 3(c)) a free running MRR to a locked one by measuring their transmission spectrum several times. Each measurement was taken 5 min apart from the other. The measurement was conducted by scanning the 980 nm tunable laser and recording the transmission over time. As can be seen, the resonance frequency of the free running MRR drifts significantly ($\sim 1$ GHz) with respect to the stabilized one, which show frequency instability lower than 200 MHz (limited by the measurement scheme).

The above mentioned result serves as a proof of concept for our ability to stabilize a laser using the proposed scheme. However, this characterization approach is limited to about 200 MHz in precision. Therefore, we now turn to a more accurate characterization of our approach. An ideal characterization scheme would be to replicate the system and beat the two 980 nm lasers. Unfortunately, such an approach would be highly challenging and costly to implement. Instead, we exploit the multi-line nature of both the MRR and the molecular transition around 1550 nm. Specifically, we measure the beat between two tunable lasers at 1.5 μm (HP 81682A). The measurement is conducted by using a fast photodetector (Agilent 11982A) followed by a high frequency counter (Agilent 53181A), having a frequency uncertainty floor level of 1 kHz, significantly beyond the precision needed for our experiment.

The following four different reference systems have been characterized by measuring the beat between the reference system and an absolute reference (laser locked to acetylene ($^{12}$C2H2) P15): 1—a free laser, 2—a laser stabilized to a free running MRR, 3—a laser stabilized to a stabilized

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**FIG. 2.** Frequency stabilization transfer scheme. Three loops are presented. Loop (a) represents a laser at 1550 nm which is locked to an acetylene line. Loop (b) describes an MRR locked to the 1550 nm laser. Finally, loop (c) shows a laser at 980 nm locked to the MRR.
MRR, and 4—a laser stabilized to a different acetylene cell (^{13}C_{2}H_{2}, P9). The measurements were analyzed by an Allan deviation produced from Stable32 software.\(^{22}\) The Allan variance, also known as two-sample variance, is a highly common measure of frequency stability in clocks, oscillators, and amplifiers. The obtained results are presented in Fig. 4.

By observing the obtained Allan deviation, one can learn that we were able to transfer the frequency stability of our acetylene cell (2.5 \times 10^{-9} around 100 s, see the red line) to another frequency line, with almost the same stability (4 \times 10^{-9} around 100 s, see the blue line). Considering our Q factor of 10^5 and a typical signal to noise of 100, our result is in line with the theoretical predictions for white noise limited system given by \(\sigma_{y}(\tau) = 0.2 \times N/QS \times \tau^{0.5}\).

The white noise assumption is justified by the slope of the Allan deviation (inverse square root dependency in short times). Furthermore, we show a significant improvement over both the free running MRR and the free running laser results, as could be anticipated. One should also mention that both the free running MRR and the stable MRR show better stability than the free laser at short times. At longer times (>8 s), the MRR begins to drifts and as expected cannot be considered as a long range frequency reference source.

It should be mentioned that the measured instability of 4 \times 10^{-9} varies only very slightly across the spectrum, due to the fact that the core and the clad of the waveguide have similar thermo-optic coefficients. As a result, the above mentioned stability of 4 \times 10^{-9} is accurate up \(\approx 1\%\) for different spectral bands.

We now discuss the potential of our approach to go beyond the achieved results. While our 50 Torr acetylene cell is characterized by a relatively broad line (\(~1\) GHz), mostly due to pressure broadening which result in a frequency stability of \(\Delta f/f = 2.5 \times 10^{-9}\), other acetylene frequency standards have been shown to have stability of \(\Delta f/f = 10^{-12}\) when using a sub-Doppler scheme with 0.015 Torr that results in a 2 MHz line.\(^{23}\) Is it possible to transfer such high stabilities to laser lines? As the stability of our system is limited by \(\sigma_{y}(\tau) = 0.2 \times N/QS \times \tau^{0.5}\), one needs to use MRR with higher Q factors, towards 10^8. The availability of such resonators implies that stabilization to the 100 Hz regime is indeed possible. Another direction for improving the frequency stability is to improve the signal-to-noise ratio of the system.

Recently, there is a growing interest in the ultrashort time stability of chip scale MRR’s, with obtained stabilities of the order of \(\Delta f/f = 5 \times 10^{-13}\).\(^{17,24}\) Our current system is characterized by a time constant of \(~100\) ms. This can be improved by implementing faster servo loops. And yet, we are also limited by the RC thermal time constant. Recent results show thermal time constants in the microsecond and even in the sub-microsecond regime.\(^{25,26}\) It should be noted, however, that at such a short timescale, one can simply use the MRR itself as a frequency reference, even without using any stabilization mechanism.

To conclude, we have demonstrated a chip scale frequency stability transfer scheme capable of replicating the frequency stability of a molecular line. By referencing an MRR to an acetylene line, we obtained multiple stable wavelength reference, at the telecom band and around 980 nm. By analyzing our data in terms of Allan deviation, we observed frequency instabilities as low as 4 \times 10^{-9} at time scales of around 100 s. Further improvement in frequency stabilization can be achieved by using a narrower molecular line accompanied by improving the Q factor and the signal-to-noise ratio of the MRR. In addition to its high precision, the molecular line provides high accuracy. As such, a proper calibration of the system would provide on chip multiple lines with high accuracy. The obtained result paves the way to important applications in the field of optical communication and metrology.

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